From groupware to large-scale trustworthy distributed collaborative systems

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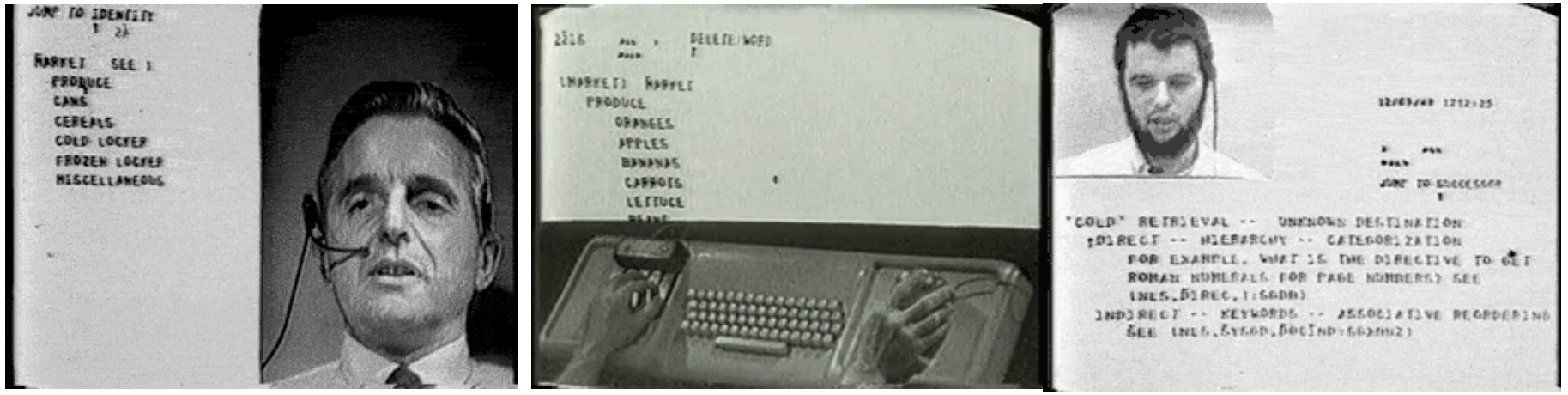
Douglas Engelbart: Augmenting Human Intellect



The Mother of all Demos, December 9, 1968

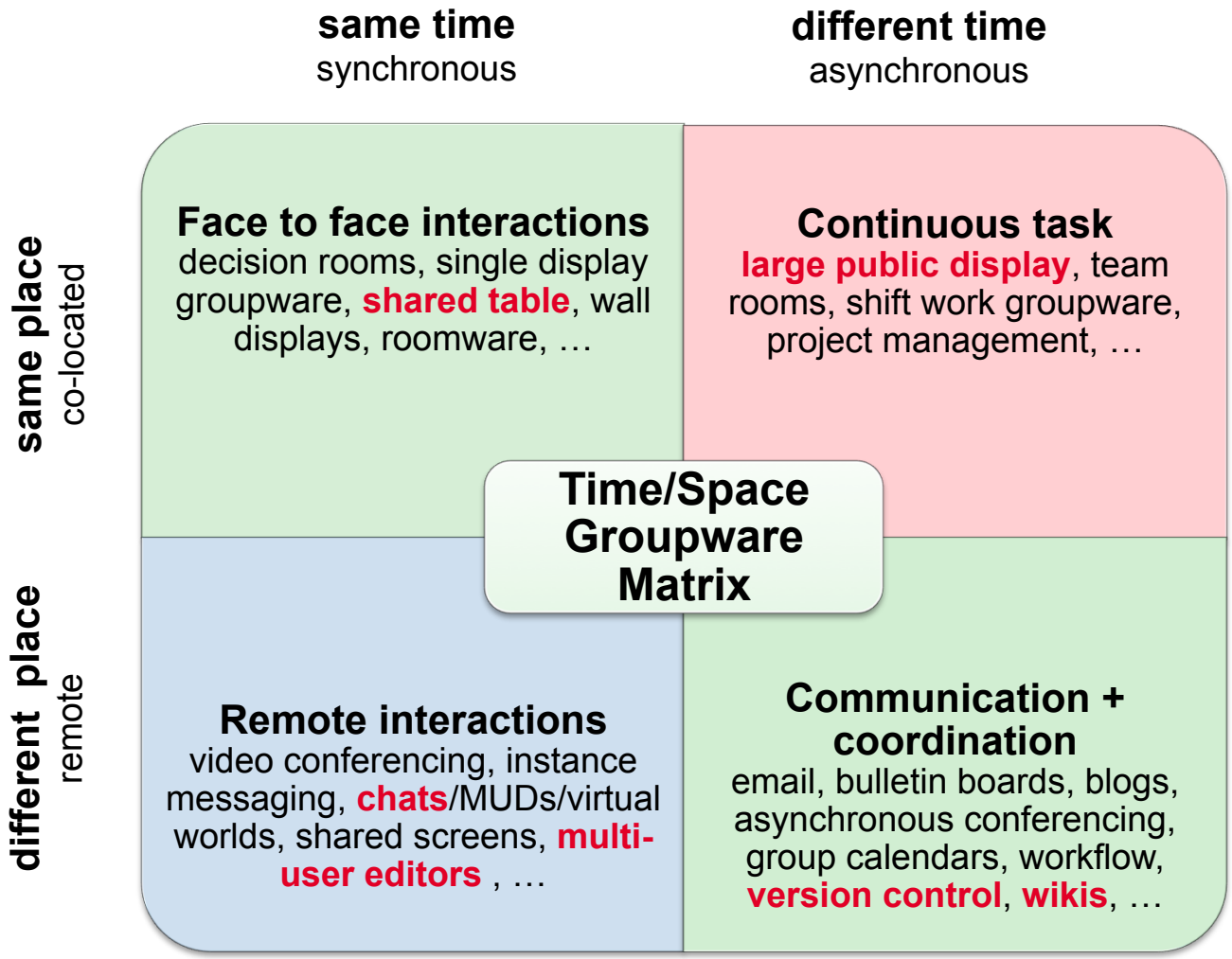
NLS: Online System

https://archive.org/details/dougengelbartarchives

Groupware, early 1990s

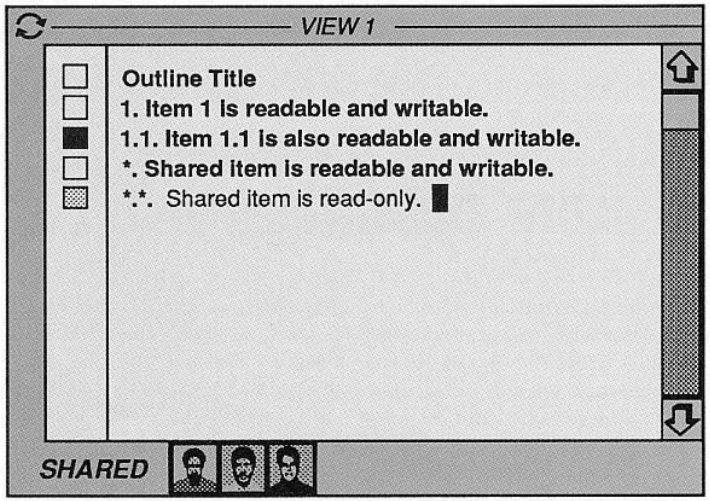
- « Computer-based systems that support groups of people engaged in a common task (or goal) and that provide an interface to a shared environment. » [EGR91]
- Lotus Notes, one of the first commercial groupware allowing remote group collaboration

Groupware Time Space Matrix [J88]



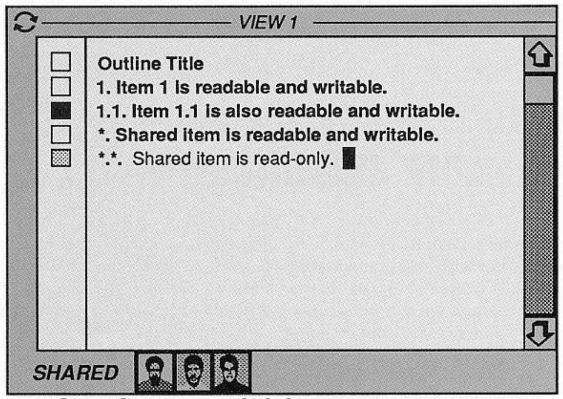
Groupware: supported solutions

- *Turn taking*: allow only one active participant at a time
  - e.g. *RTCAL* [SG88], *SHARE* [G90]
- *Locking*: concurrent editing allowed only if users lock and edit different objects
  - e.g. *Colab* [SFBKLS88]
- *Operational transformation*
  - e.g. *GROVE* [EG89]



Google Drive

Collaborative Systems: from users to community of users



GROVE, 1989

"Isn't it chaotic to all edit in the same document, even the same paragraph, at the same time?"

"Why would a group ever want to edit in the same line of text at the same time?" [EGR91]

Collaborative Systems: from users to community of users

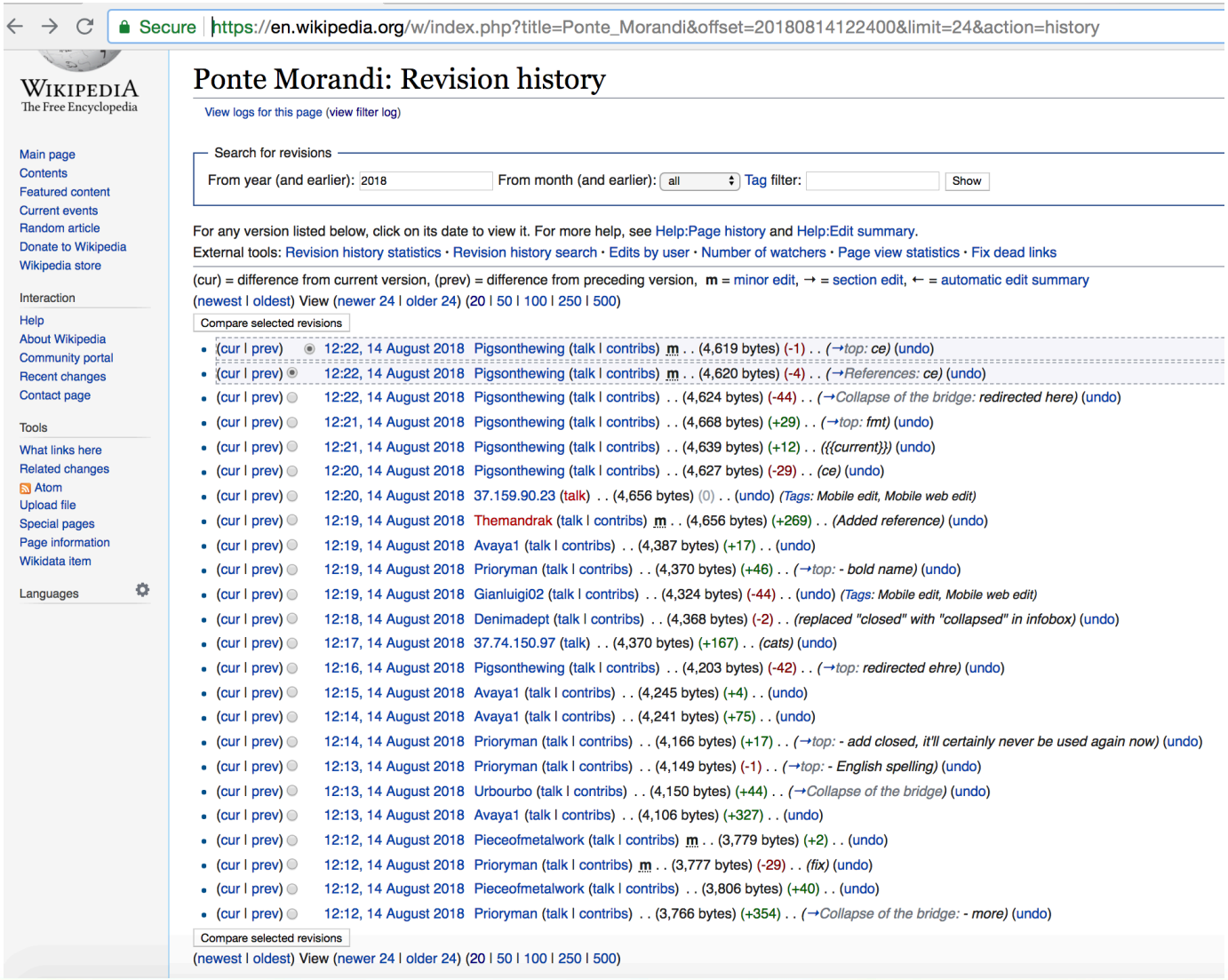
2013: MOOC “Fundamentals of Online Education: Planning and Applications” with 40.000 participants

2016: Nuit debout, more than 70 people edit a pad

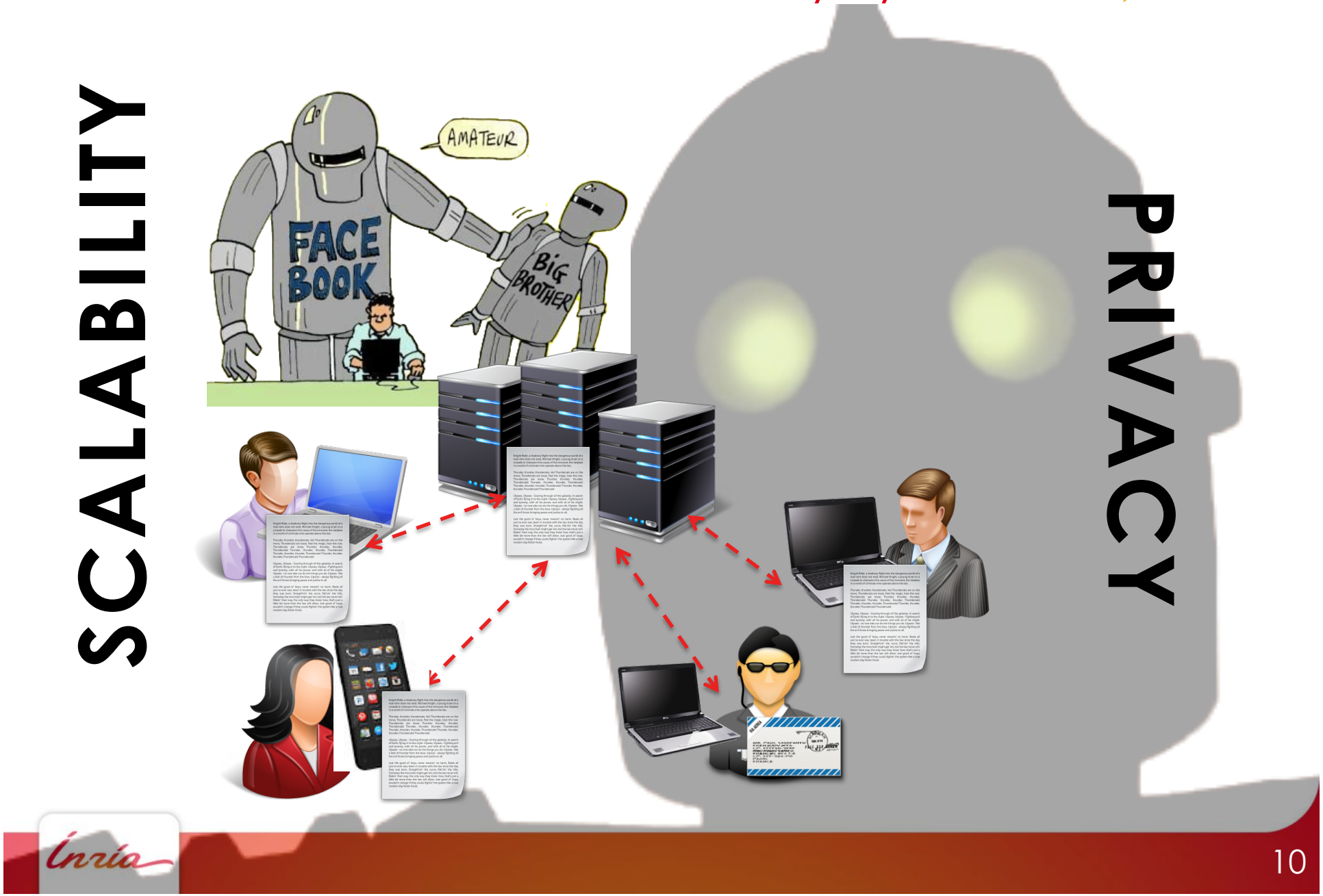
2018: online CSCW PC meeting with 120 members

Collaborative Systems: from users to community of users

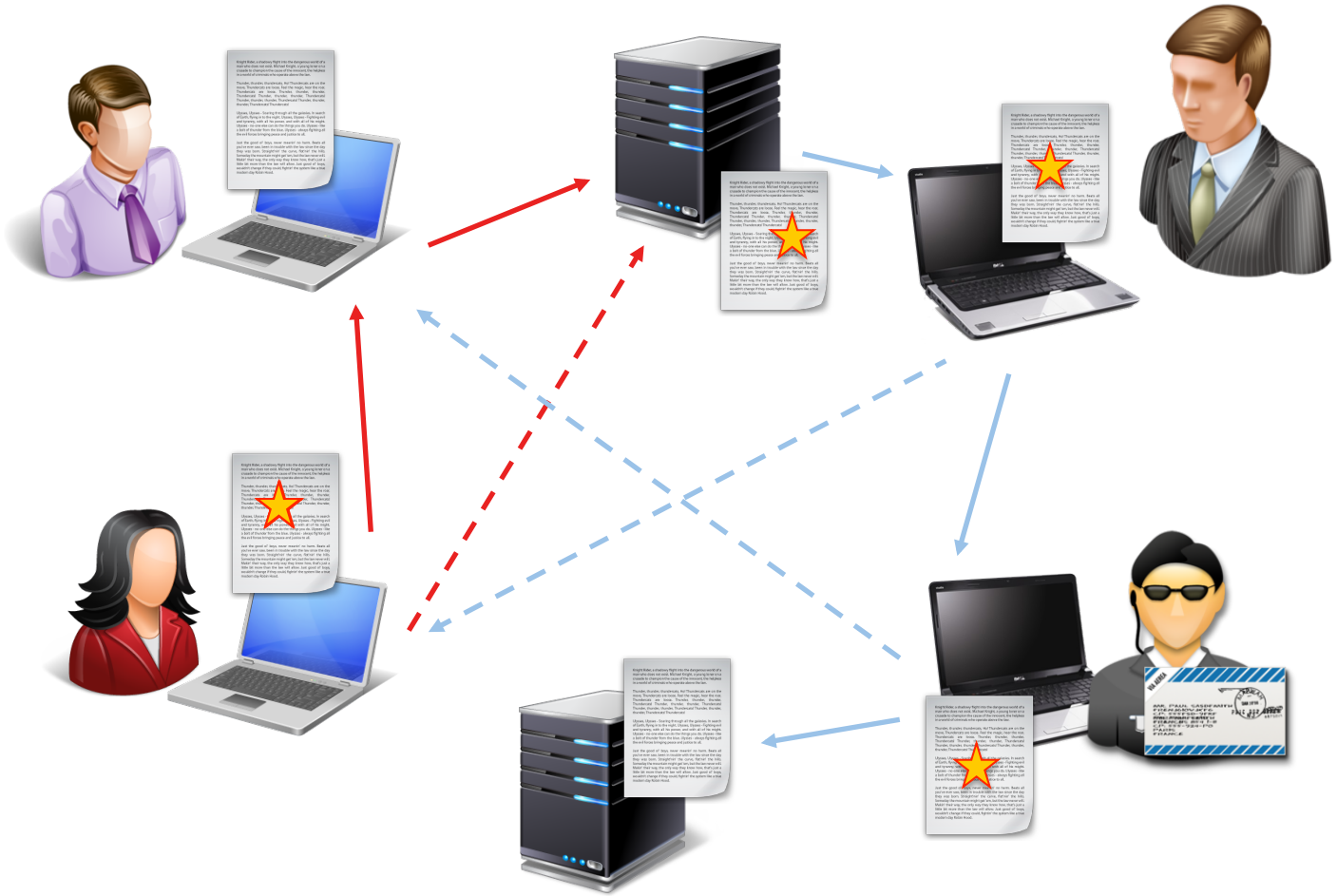
Real-time Wikipedia



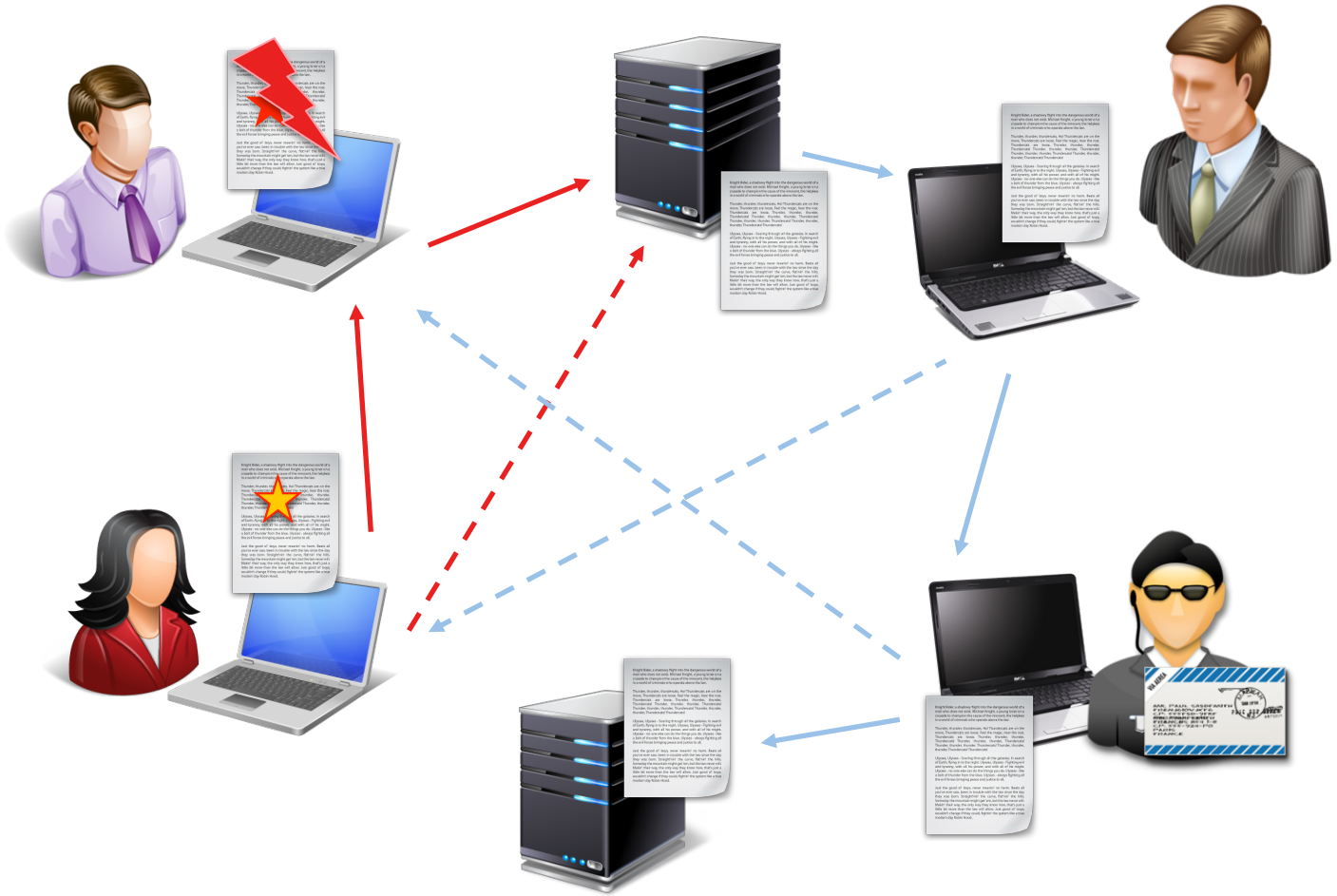
Limitations of Central Authority Systems



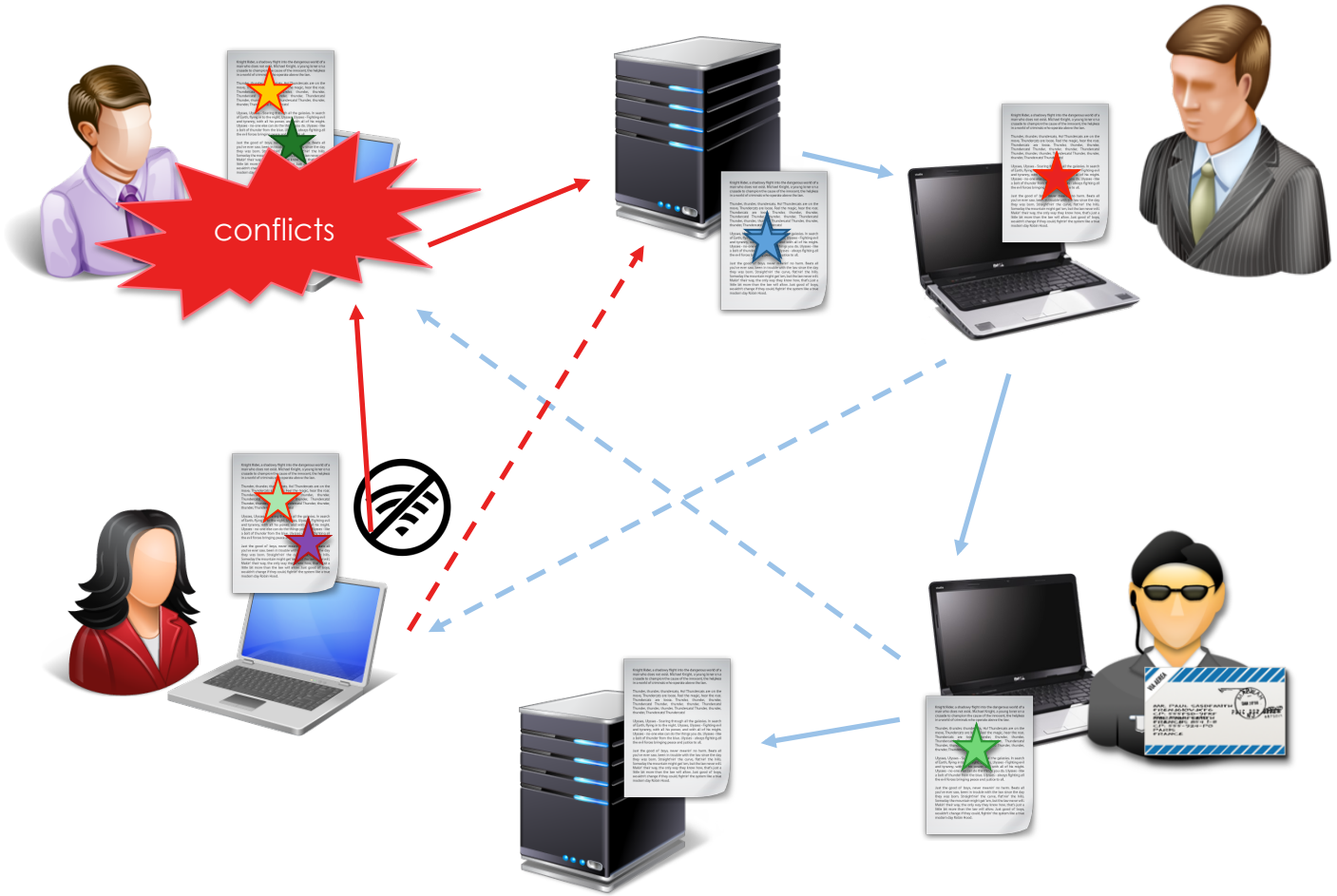
Peer-to-Peer Collaborative Systems



Collaboration Modes – Concurrent Changes



Collaboration Modes – Offline Work



Collaboration Modes – Ad-hoc Collaboration

Research issues

1. How to **maintain consistency of different copies** in the face of concurrent modifications?

2. How to **evaluate the design of collaborative systems** and approaches?

3. How to **secure collaboration data**?

Research issues

1. How to **maintain consistency of different copies** in the face of concurrent modifications?

2. How to **evaluate the design of collaborative systems** and approaches?

3. How to **secure collaboration data**?

Optimistic Replication [SS05]

- Trade-off between consistency and availability
  - Optimistic replication : allows replicas to diverge
- Strong Eventual Consistency
  - Eventual delivery: An update executed at some correct replica eventually executes at all correct replicas
  - Strong convergence: Correct replicas that have executed the same updates have equivalent states
  - No consensus in background, no need to rollback
- Intention preservation
  - « *Effect of each operation should be observed on all copies* »

Operational transformation (OT) [EG89]

- *n* copies of an object hosted at *n* sites
- An object is modified by applying operations

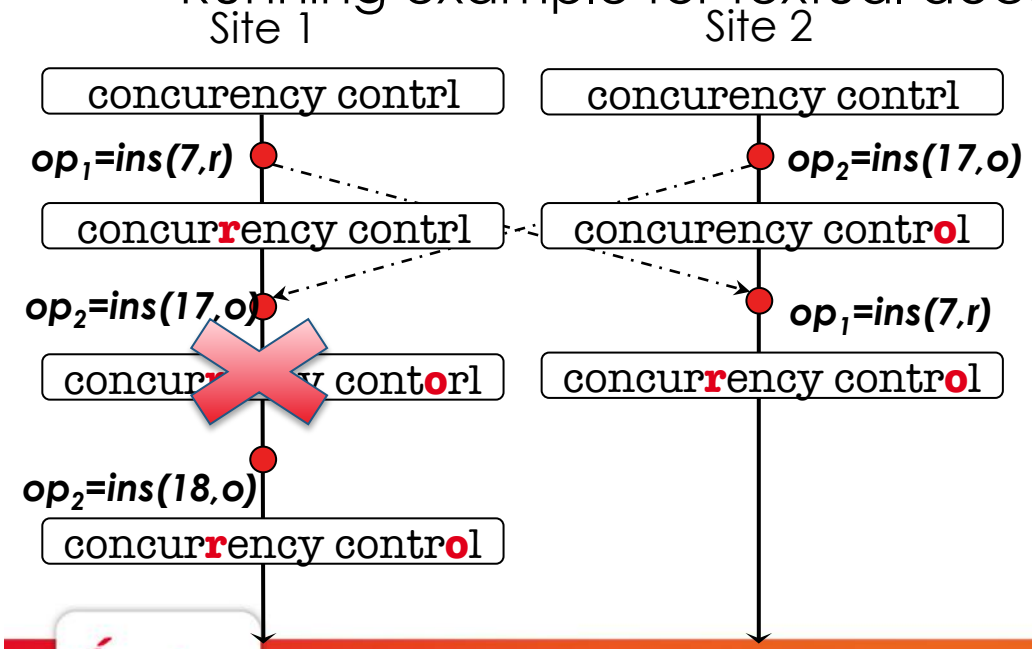
- Each operation is
  - generated at a site (local execution),
    and applied immediately on the local copy
  - broadcasted to other sites
  - integrated at those sites (remote execution)

- System is correct if when it is idle all copies are identical (SEC)

Operational transformation (OT)

- General architecture with two main components:
  - An integration algorithm (diffusion, integration)
  - A set of transformation functions (conflict resolution)

- Running example for textual document = sequence of characters

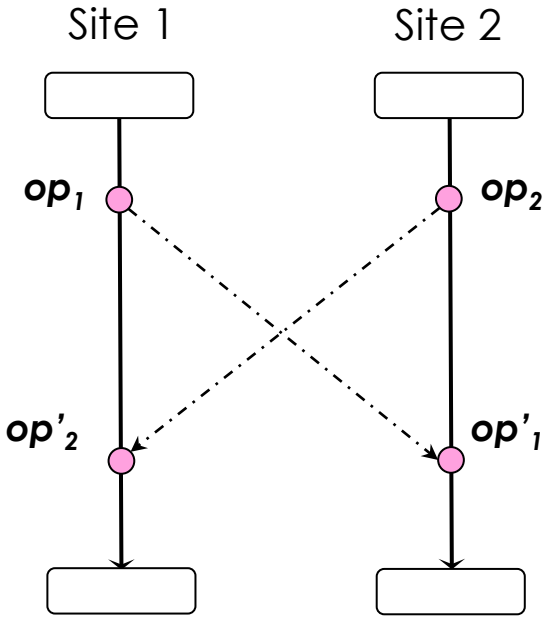


- Operations:
  - ins(p, c)
  - del(p)

```
T(ins(p1,c1), ins(p2,c2)) :-
  if (p1<p2) return ins(p1,c1)
  else return ins(p1+1,c1)
  endif
```

Operational transformation
Correctness [EG89]

(TP1) $op_1 \circ T(op_2, op_1) \equiv op_2 \circ T(op_1, op_2)$

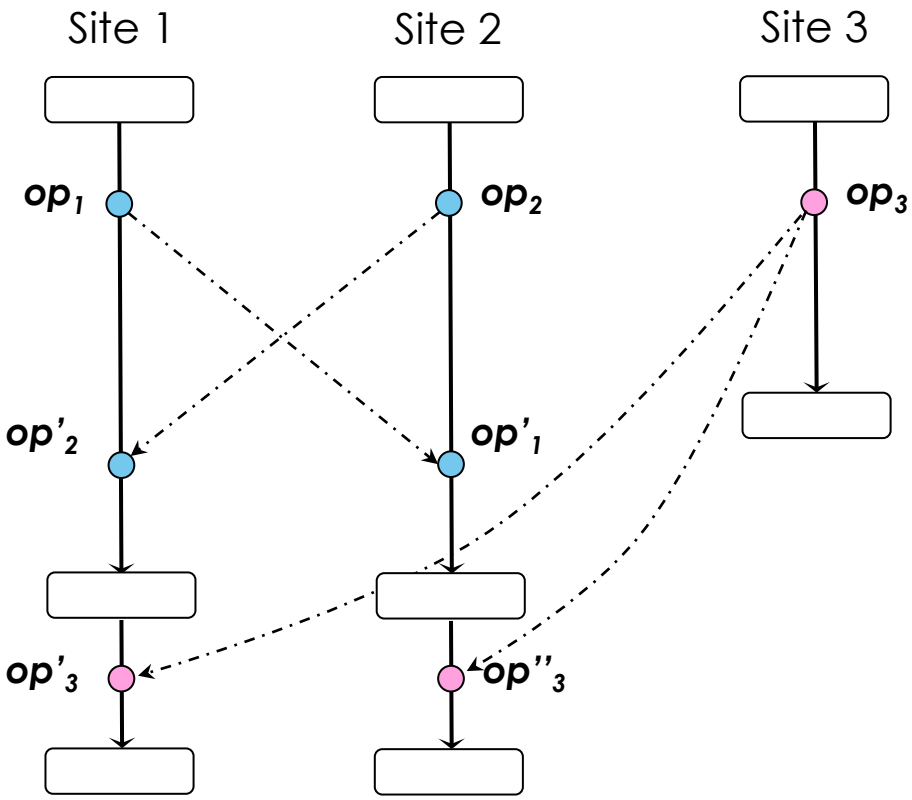


T(op_2: operation, op_1: operation) = op'_2

- op_1 and op_2 concurrent, defined on a state S
- op'_2 same effects as op_2, defined on S.op_1

Operational transformation
Correctness [RNG96]

(TP2) $T(op_3, op_1 \circ T(op_2, op_1)) = T(op_3, op_2 \circ T(op_1, op_2))$



Operational transformation (OT)
Existing approaches

- Two main families:
  - Transformation functions satisfying both TP1 and TP2: SOCT2 [SCF97] + TTF [OUMI06]
  - Control algorithms avoiding (needs of) TP2: SOCT4 [VCFS00], Jupiter [NCDL95]

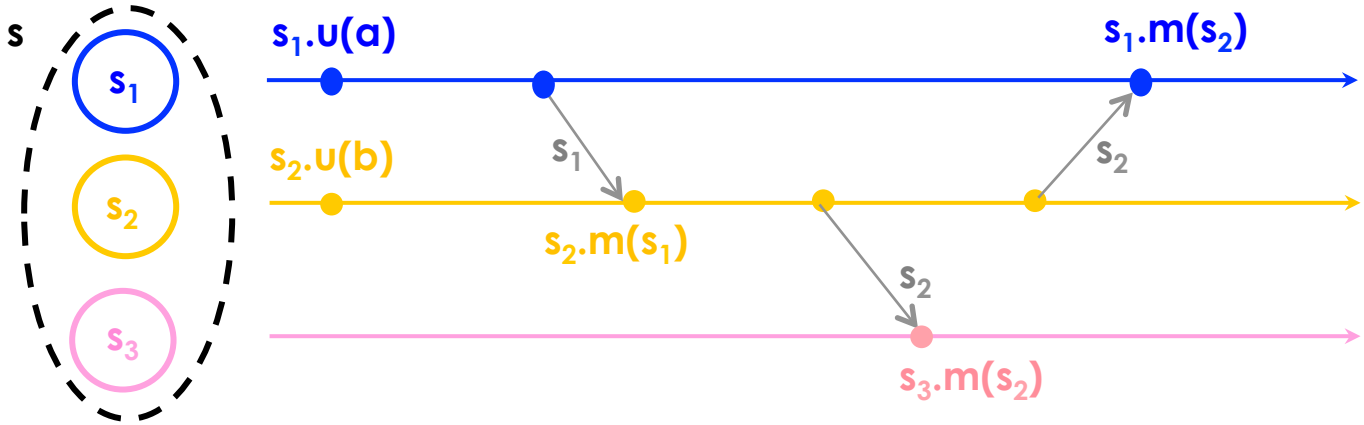
Operational transformation (OT)
Summary

- Transforms non commuting operations to make them commute
- Genericity
- Time complexity
  - Average: O(H c) H: #ops
  - Worst case: $O(H^2)$ c: avg. #conc. ops
- Difficult to write correct transformation functions
- State vectors used for detecting concurrency ⇒ scalability limitations
- **Not very suitable for large scale peer-to-peer collaboration**

Conflict-free Replicated Data Types (CRDT) [SPBZ11]

- Design operations to be commutative by construction
- Abstract data types
  - Designed to be replicated at multiple sites
  - Any replica can be modified without coordination
  - State convergence is guaranteed
- State-based and operation-based approaches

Conflict-free Replicated Data Types (CRDT)
State-based Replication



- Algorithm
  - Periodically, replica at p_i sends its current state to p_j
  - Replica p_j merges received state into its local state by executing m
- After receiving all updates (irrespective of order), each replica will have same state

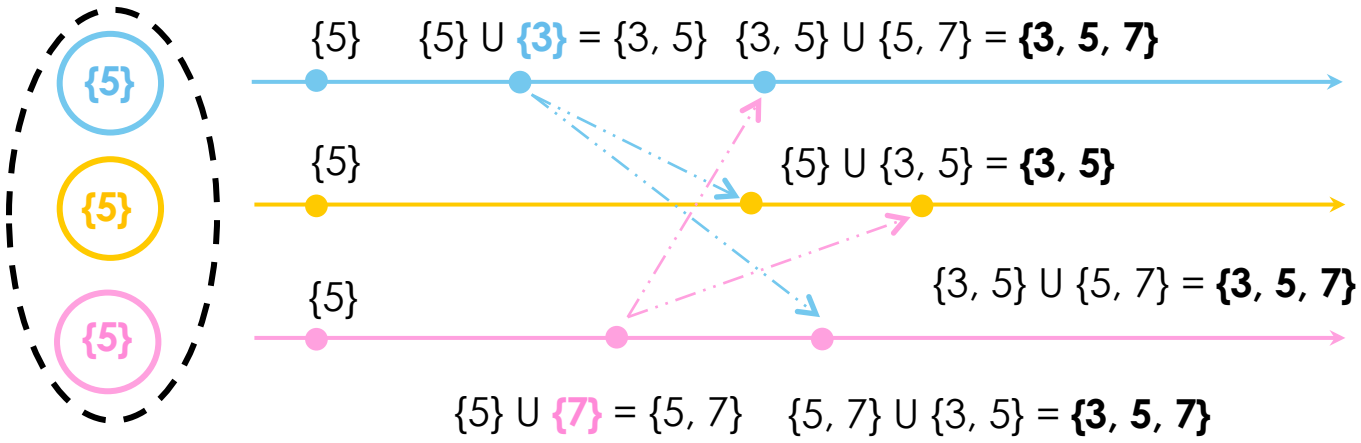
Conflict-free Replicated Data Types (CRDT)
State-based Replication

- Merge operator:
  - **Commutative**: $x \bullet y = y \bullet x$
  - **Associative**: $(x \bullet y) \bullet z = x \bullet (y \bullet z)$
  - **Idempotent** : $x \bullet x = x$

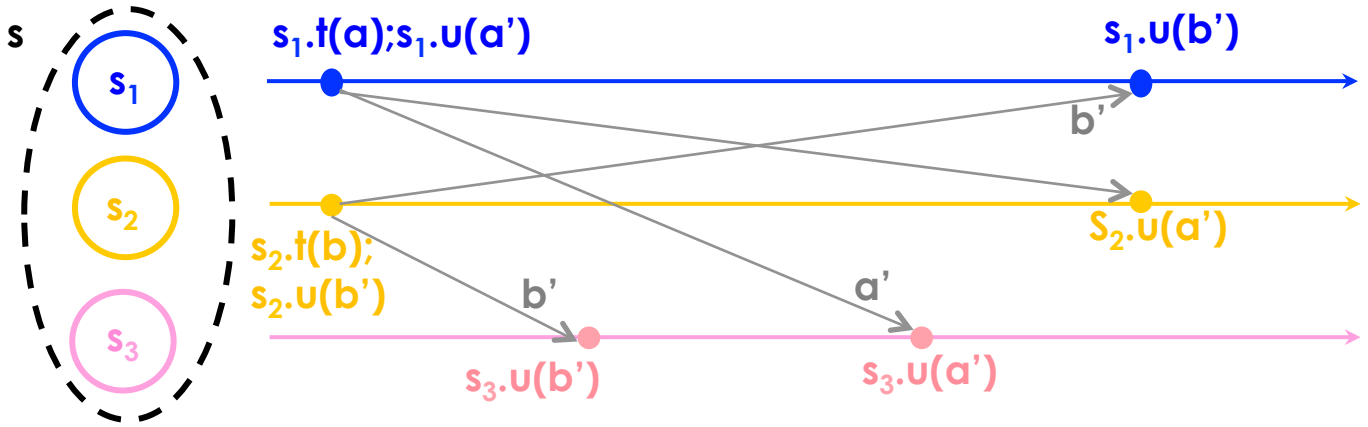
- A semi-lattice is a Partial order $\leq$ set S with a least upper bound (LUB), denoted $\sqcup$
  - $m = x \sqcup y$ is a LUB of $\{ x, y \}$ under $\leq$ if and only if
    $\forall m', x \leq m' \wedge y \leq m' \Rightarrow x \leq m \wedge y \leq m \wedge m \leq m'$
  - It follows that $\sqcup$ is commutative, associative and idempotent

Conflict-free Replicated Data Types (CRDT)
Convergent Replicated Data Type (CvRDT)

- Example



Conflict-free Replicated Data Types (CRDT) Operation-based Replication



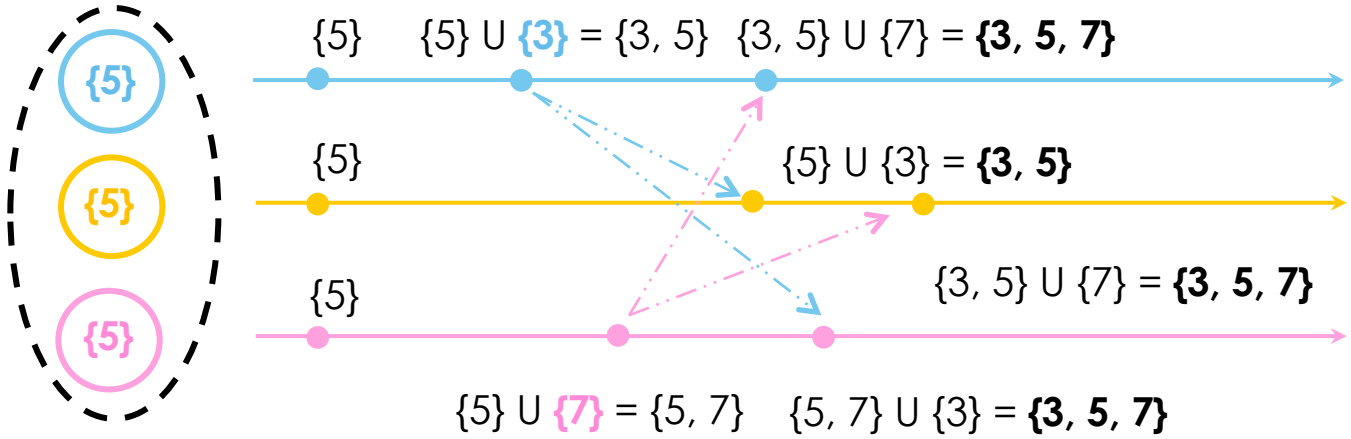
- An update split into *(t,u)*: *t* is a side-effect-*free prepare-update method* and *u* is an *effect-update* method

- Algorithm
  - Updates delivered to all replicas
  - Causally-ordered broadcast, every message delivered to every node exactly once w.r.t. happen-before order

- Commutativity holds for concurrent updates

Conflict-free Replicated Data Types (CRDT)
Commutative Replicated Data Type (CmRDT)

- Example



Conflict-free Replicated Data Types (CRDT) CvRDT vs. CmRDT

- Both approaches are equivalent
  - A state-based object can emulate an operation-based object, and vice-versa
- Operation-based:
  - More efficient since you only ship small updates
  - But require exactly once causally-ordered broadcast
- State-based:
  - Only require reliable broadcast
  - Communication overhead of shipping the whole state
- Delta State-based [ASB18]:
  - Small messages
  - Dissemination over unreliable communication channels

Consistency Maintenance
Conflict-free Replicated Data Types (CRDT)

- Register
  - Last-Writer Wins
  - Multi-Value
- Set
  - Grow-Only
  - 2-Phase
  - Observed-Remove
  - Observed-Update-Remove
- Map
- Counter
- Graph
  - Directed
  - Monotonic DAG
  - Edit graph
- **Sequence**

ATOM

Conflict-free Replicated Data Types (CRDT)
(Text) Sequence [PMSL09] [WUM09]

- Document = linear sequence of elements
  - Each element has a unique identifier
  - Identifier constant for the lifetime of the document
  - Dense total order of identifiers consistent with element order:
    - $\forall\, id_x, id_y: id_x < id_y \Rightarrow \exists\, id_z : id_x < id_z < id_y$

- Different approaches for generating identifiers:
  - TreeDoc, Logoot, LogootSplit, …

Conflict-free Replicated Data Types (CRDT)
Logoot [WUM09]

- Logoot identifiers: $\langle p_1,s_1,h_1\rangle\langle p_2,s_2,h_2\rangle \cdots \langle p_k,s_k,h_k\rangle$

  p_i integer

  s_i site identifier

  h_i logical clock at site s_i

<1,2,1>	c
<1,2,2>	o
<2,1,2>	n
<3,1,3>	c
<3,1,3><8,4,5>	u
<3,2,5>	r
<4,1,7>	e
<4,1,7><9,2,6>	n
<7,2,8>	c
<9,1,7>	y
<10,2,8>	
<12,3,1>	c
<12,3,1><6,5,1>	o
<12,3,1><7,8,2>	n
<12,3,1><7,8,2><12,3,5>	t
<12,3,1><7,8,2><13,3,6>	r
<12,3,1><7,8,2><14,3,7>	l

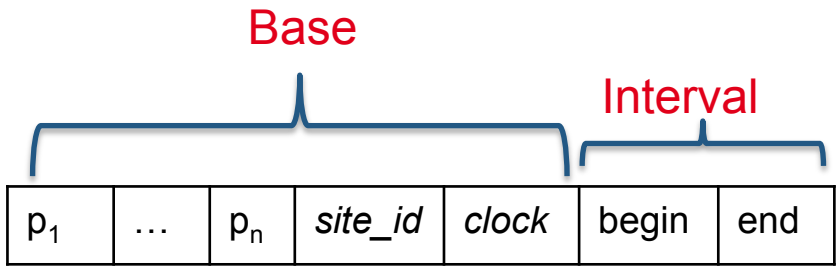
ins(<3,2,5><13,1,7>, r)

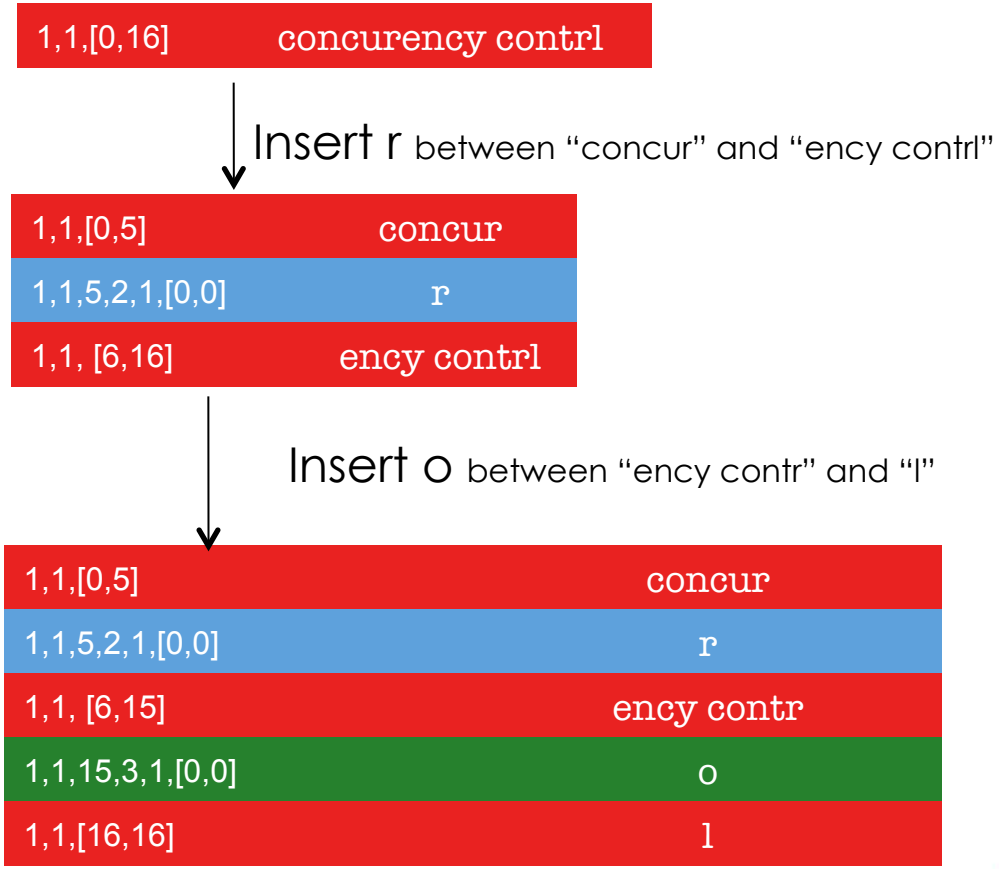
ins(<12,3,1><7,8,2><13,3,6><7,2,9>, o)

- Time complexity
  Average: O(k log(n))
  Worst case: O(H*log(H))
  H: #ops
  n: doc. size (non deleted chars.)
  k: avg. size of Logoot identifier
- No need for concurrency detection
- Identifiers storage cost
- New design for each data type
- **Suitable for large-scale collaboration**

Conflict-free Replicated Data Types (CRDT)
LogootSplit [AMOI13]

LogootSplit identifiers

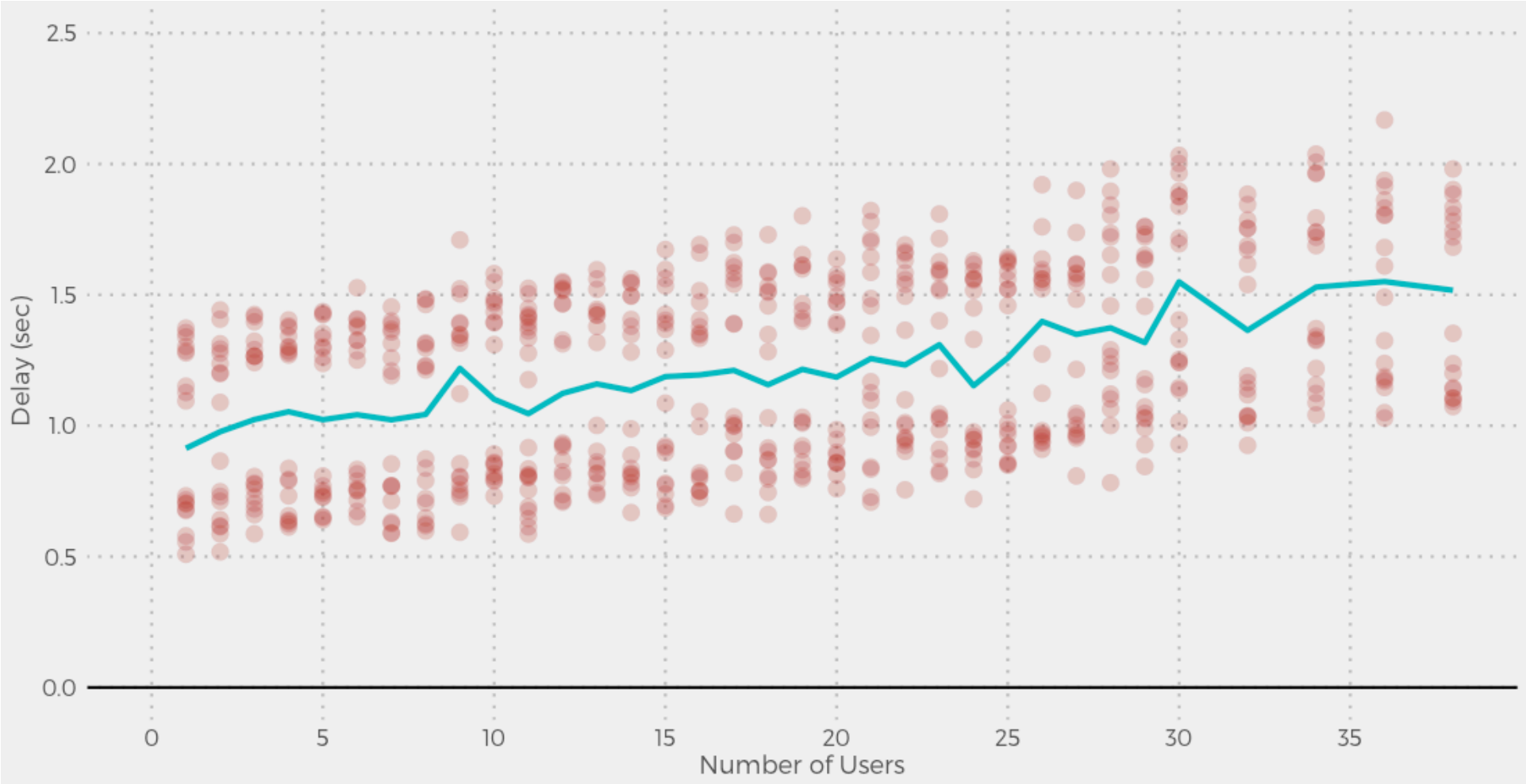




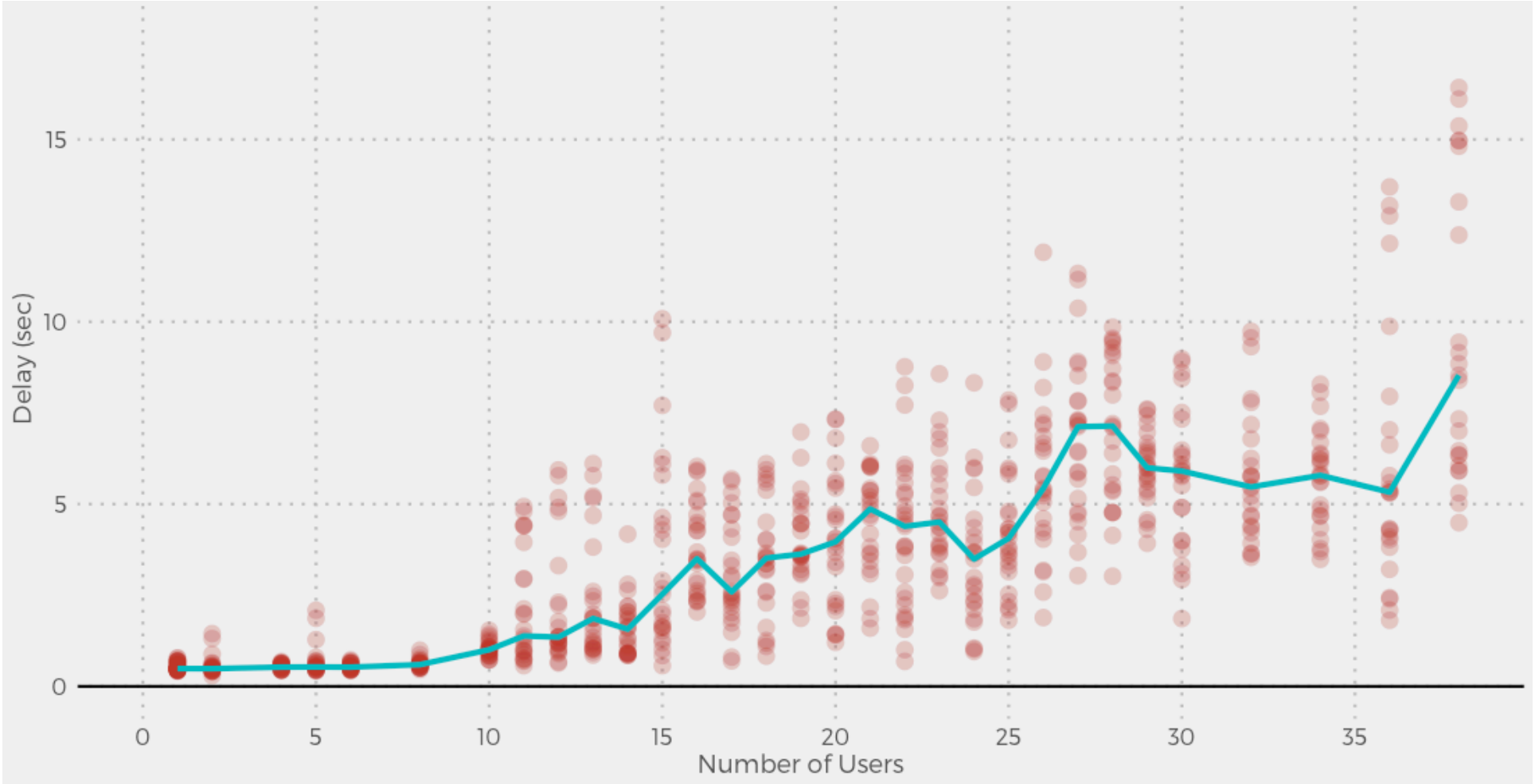
OT vs. operation-based CRDT

- CRDT: more formalised approach
- OT: more generic and guided
  - Generic concurrency control algorithm
  - Operation transformations specific to application domain
- CRDT: different solutions for concurrency handling for different data types
- CRDT: Metadata overhead

Delays in MUTE [NEOIC17] https://coedit.re/



Delays in GoogleDocs [DI16]



Research issues

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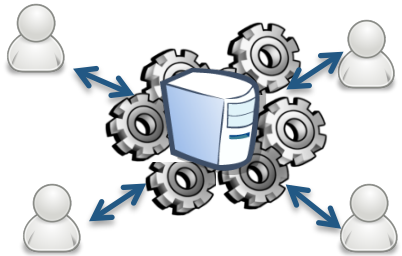
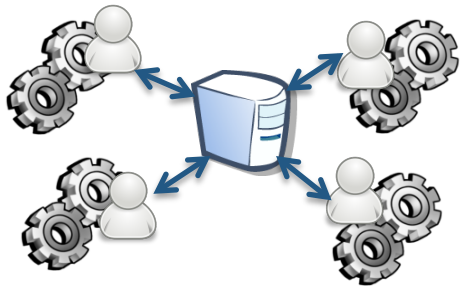
User Study: The effect of delay on users

- Delays in seeing modifications of other users
  - Network delay
  - Time complexity of consistency maintenance algorithms
  - Types of architecture



Thin client architecture



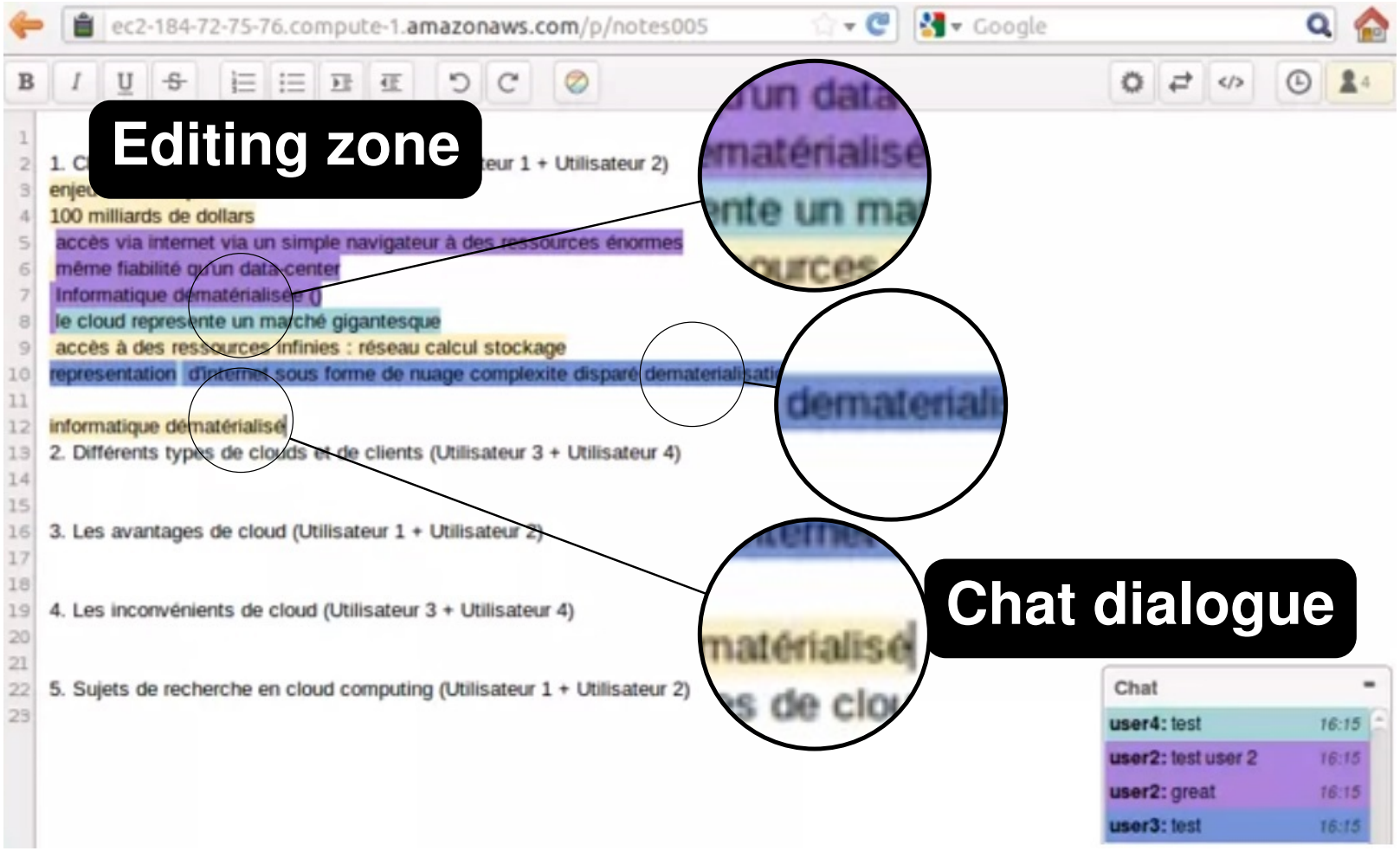
Thick client architecture

- How does **delay influence group performance**?

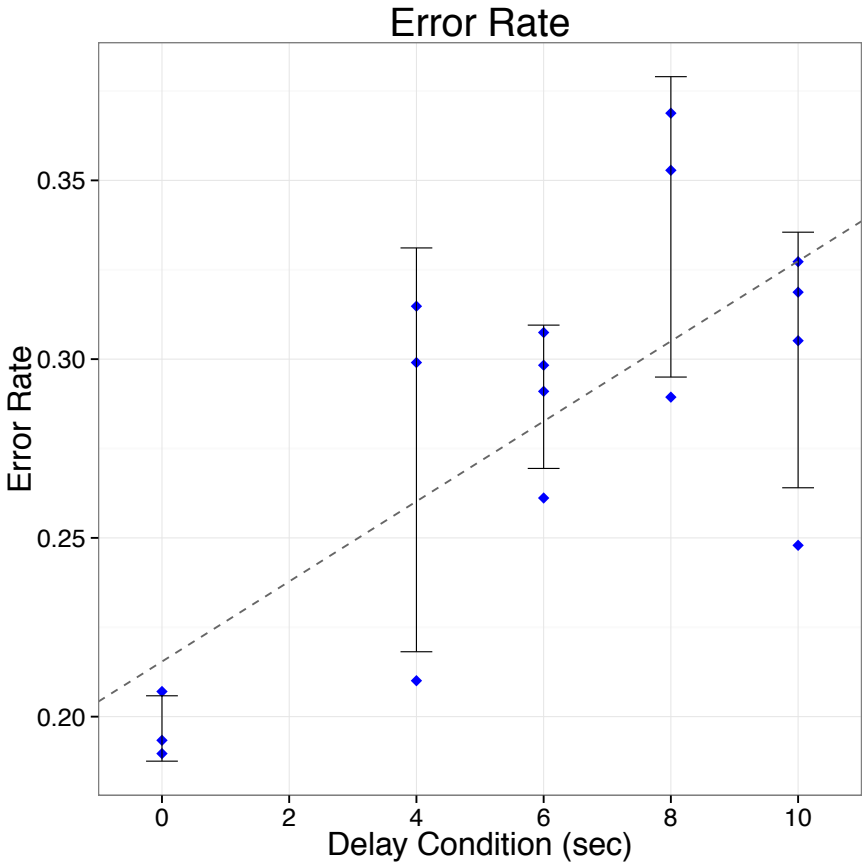
Experiment design

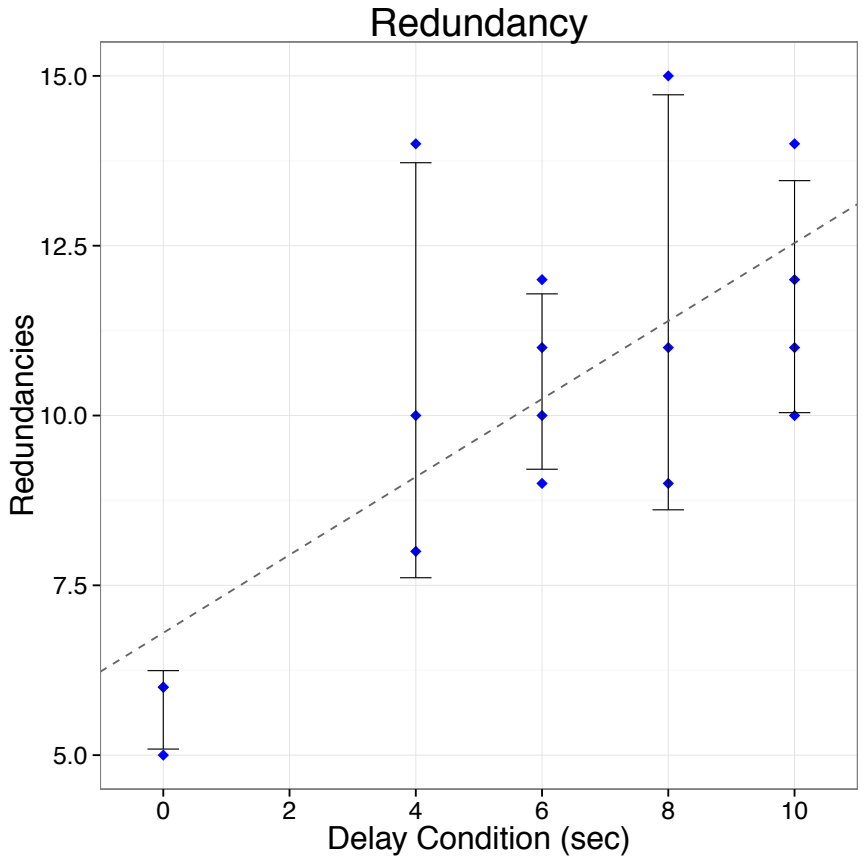
- 20 groups of 4 students
  - Perform several collaborative editing tasks
    - A proofreading task
    - A sorting task
    - **A note taking task**
  - Use the provided collaborative editor (Etherpad) + chat
  - Each group experienced a **certain delay** (0, 4, 6, 8, 10 s)
- Registration of user keyboard inputs
- Video recording of user activities on desktop

Note-taking [IOFSC15]



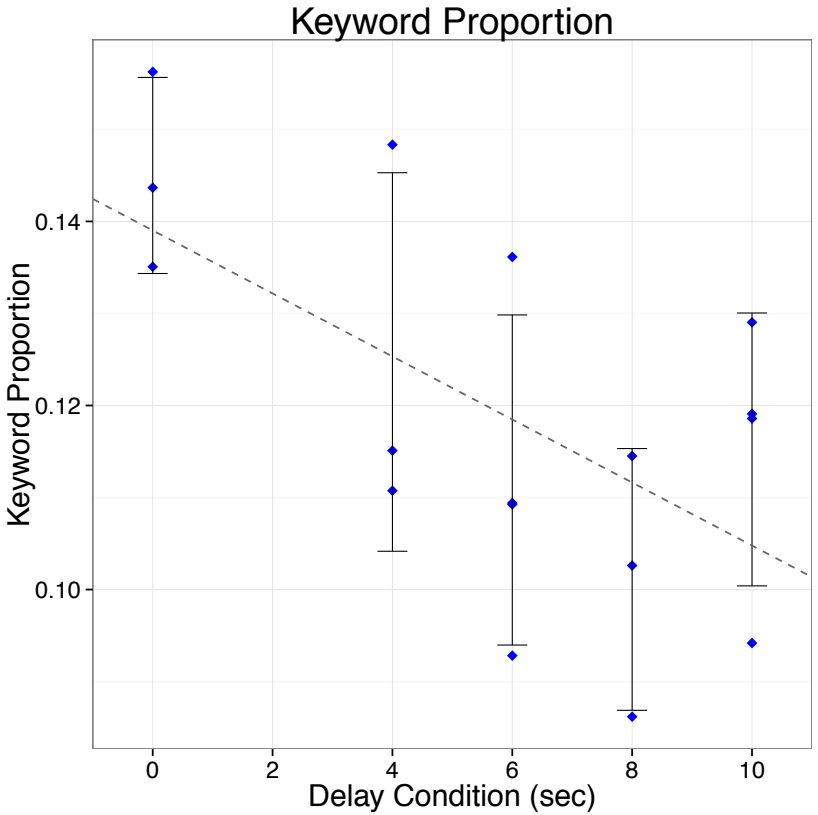
Delay reduces Group Performance





- Delay increases error rate and redundancy

Delay reduces Group Performance



- Delay decreases proportion of keywords

Design implications

- Reduce the delay by the choice of the architecture and synchronisation algorithms
- Make users aware of existing delays such that they can compensate for the delay by coordination strategies
- Analyse real collaboration traces to understand collaboration patterns and behavior [NI18]

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Security in peer-to-peer collaboration

- How to learn and verify the other party's key ?
- Trust-based access control

Trust establishment

- How to learn and verify the other party's key before establish a secure communication channel ?
  - Out of band trust establishment
  - Trust establishment by the provider

Out of band trust establishment

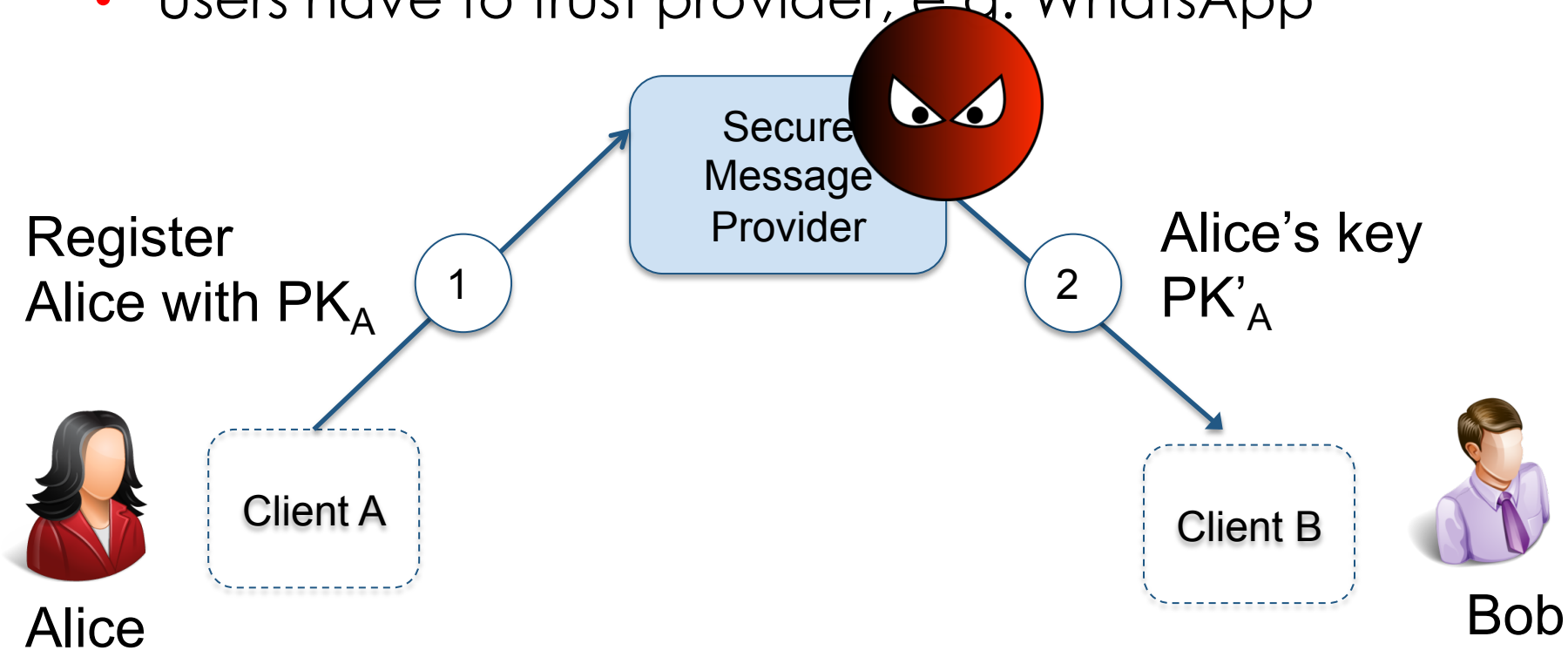
- Unintuitive, error-prone

Bob

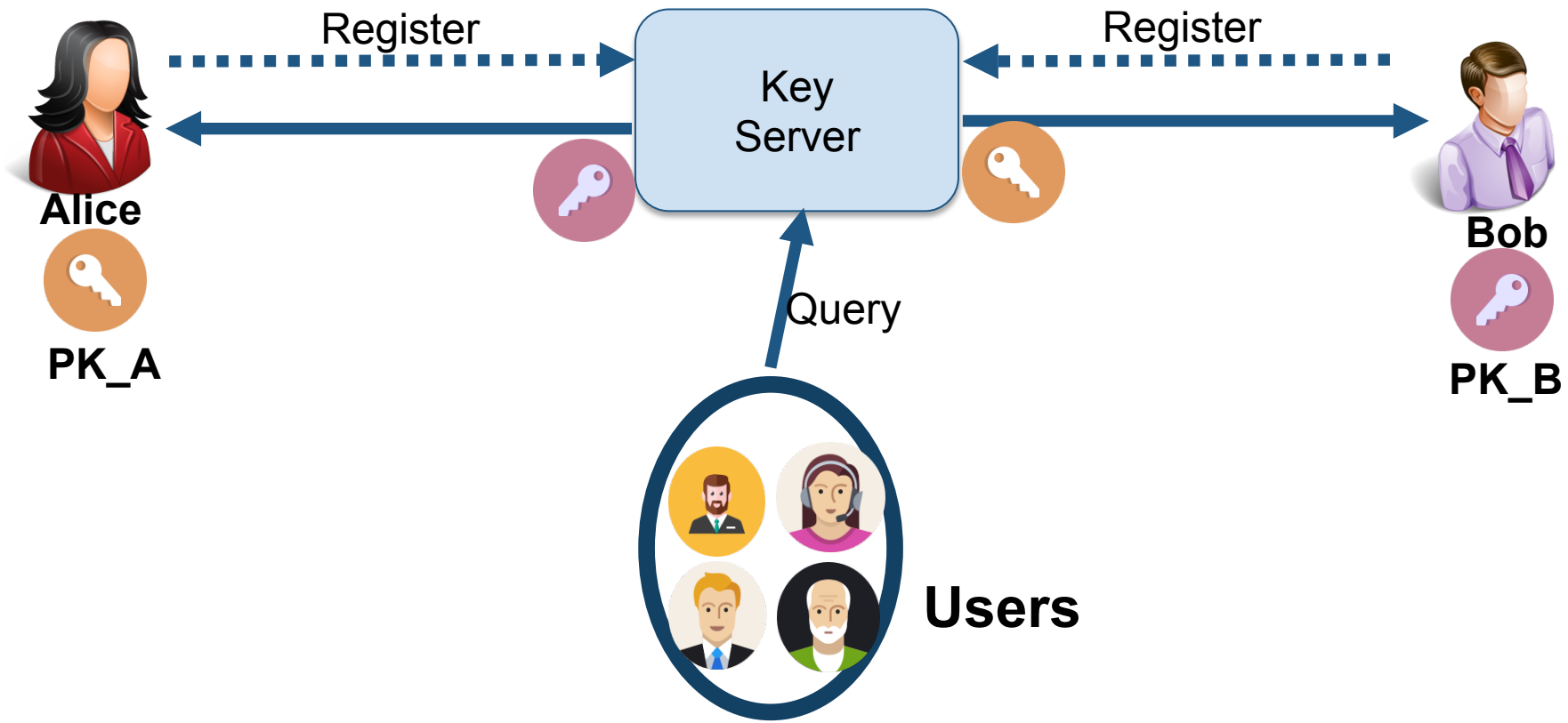
Alice

Trust establishment by the provider
Centralized key server

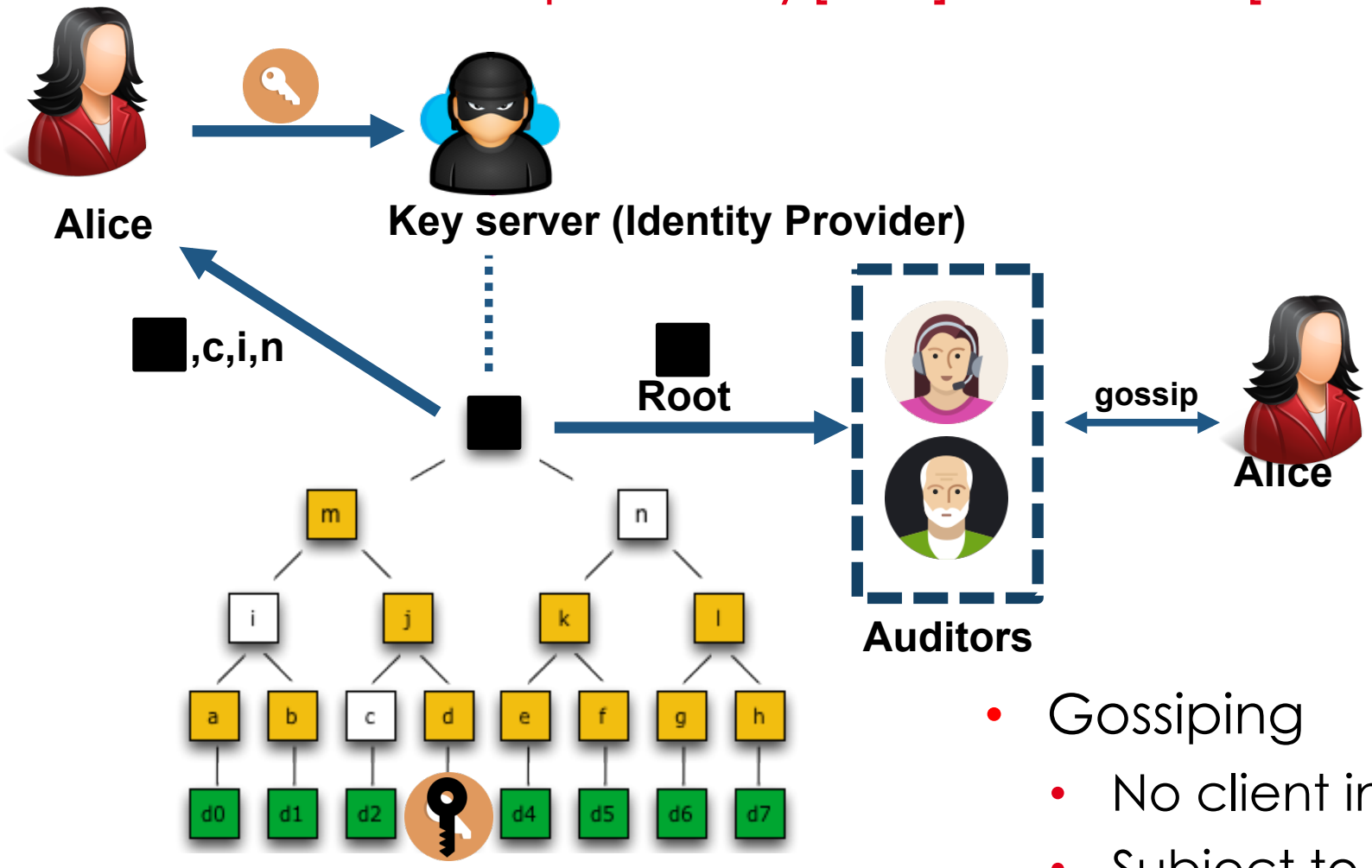
- Clients query providers for keys of other users
- Users have to trust provider, e.g. WhatsApp



Transparent log

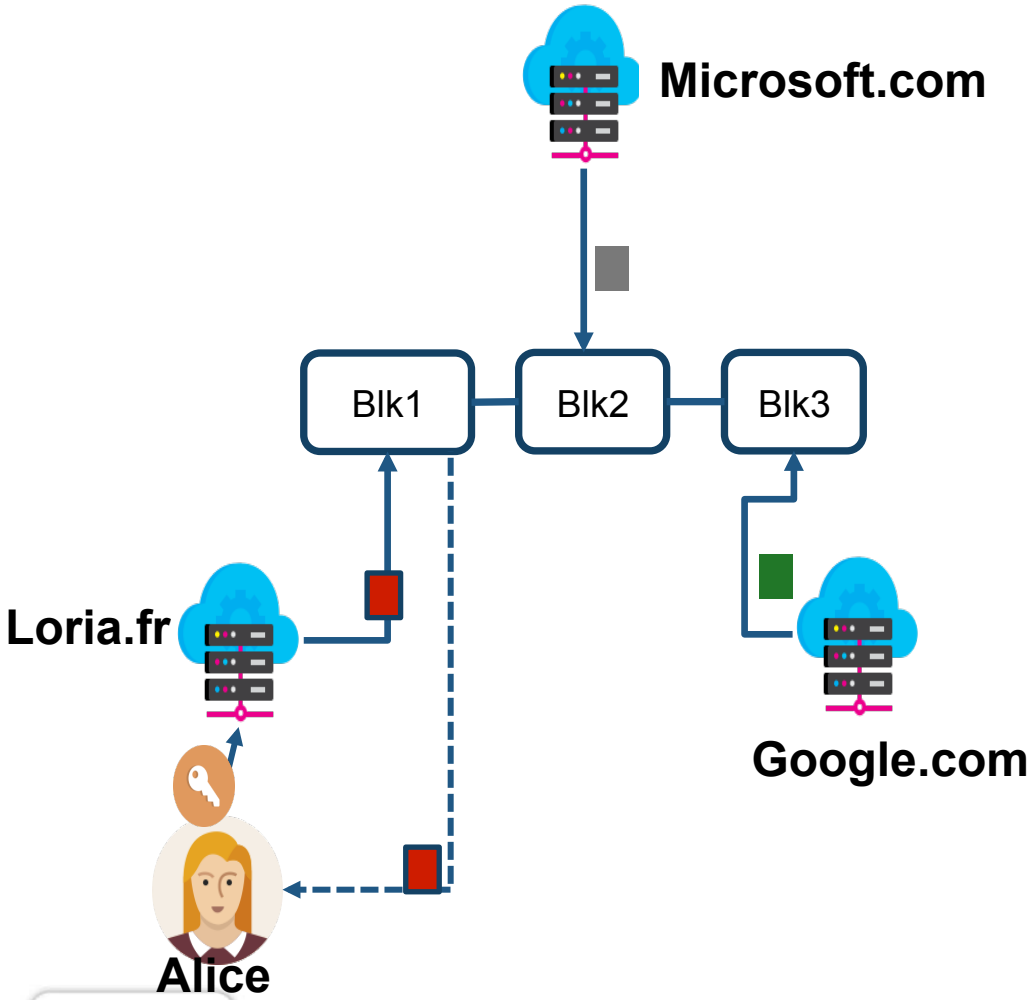


Certificate transparency[L14]/CONIKS [MBBFF15]



- Gossiping
  - No client incentive
  - Subject to Sybil and Eclipse attacks

Trusternity: Blockchain-based Auditing of Transparent Log Servers [NEIP18]

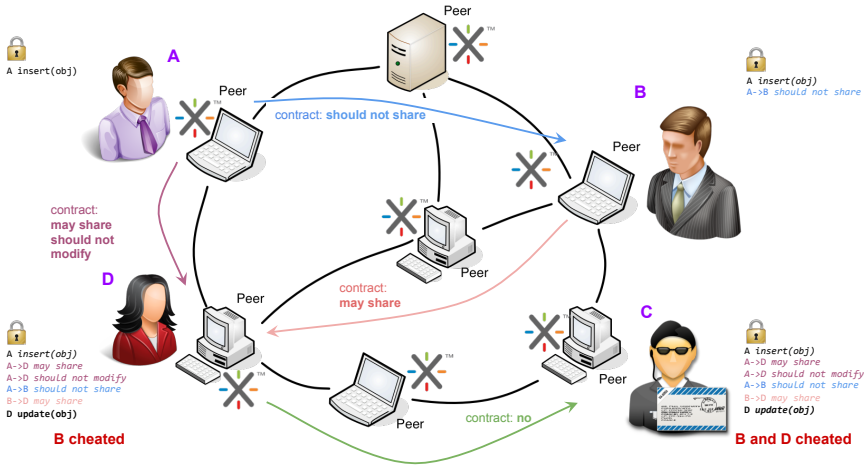


Trust-based access control

- Dynamic trust values among users
- *How to* ***define an access control based on trust*** *and how to* ***compute trust based on collaborative experience****?*

Trust computation

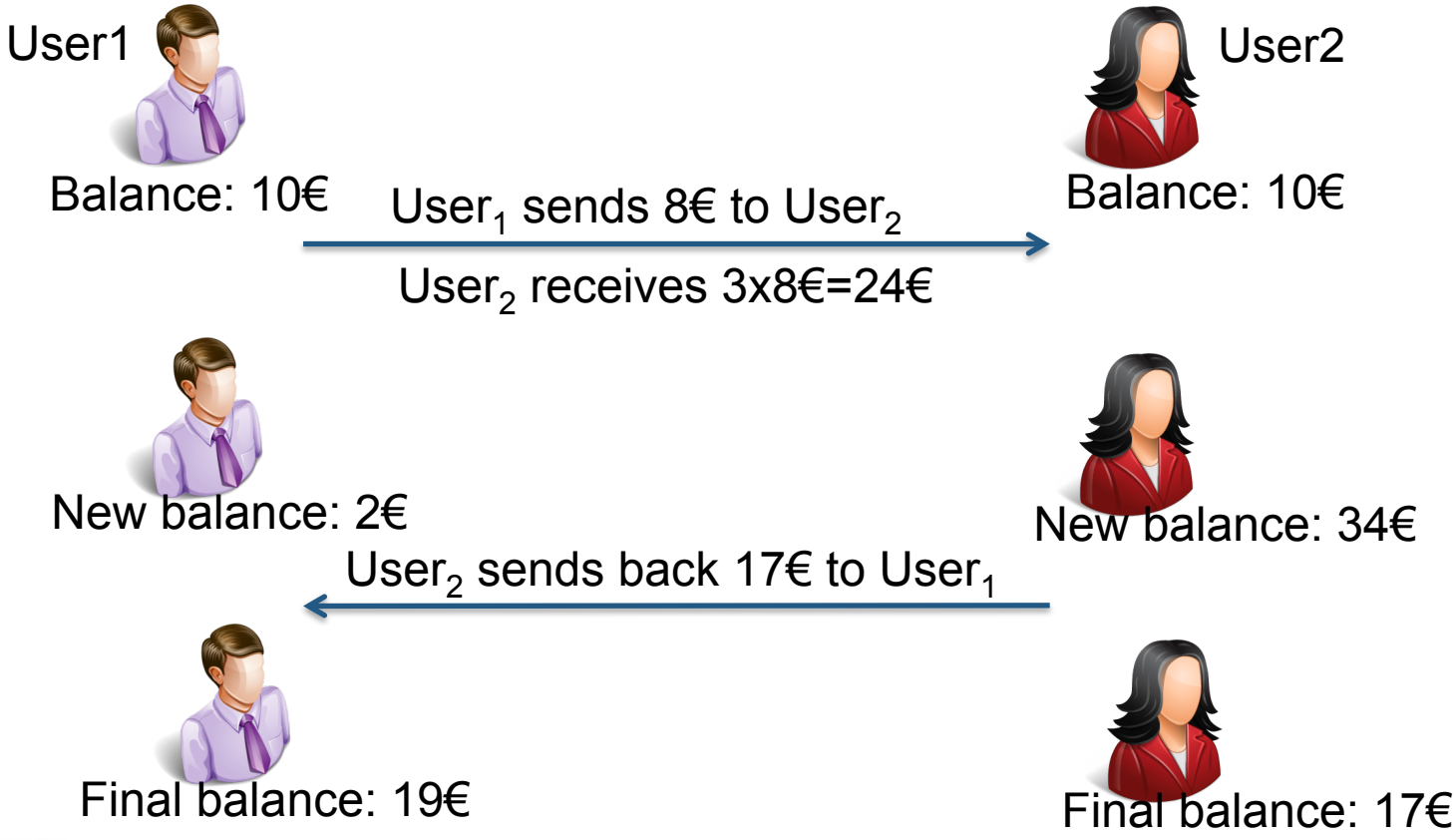
- Respect/Violation of contracts
  - Contracts in collaborative editing (share, edit)



- Reporting of fake news in Facebook
- Quality of user contributions

Validation of trust-based collaboration

- Using game theory (trust game) [BDM95]



Validation of trust-based collaboration

- Proposal of a trust metric reflecting user behavior [DI16]
- User studies on various trust game variations
  - Trust can replace knowing the identity of collaborators
  - People take into account the trust value of the partner in their future collaboration

Large-scale trustworthy distributed collaborative systems

- New uses and new practices due to large scale adoption
- New challenges
  - Consistency of replicated data
  - User studies
  - Trust and Security

References

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Thank you

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